GUGGENHEIM AERONAUTICAL LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

HYPERSONIC RESEARCH PROJECT

Memorandum No. 48

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OPERATION AND PERFORMANCE OF A SHOCK TUBE WITH HEATED DRIVER

by

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ARMY ORDNANCE CONTRACT NO. DA-04-495-Ord-19

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ABSTRACT

A shock tube was constructed with a driver section which could be heated with "Calrod" heaters to temperatures of approximately 300°C. This temperature rise increased the shock wave Mach number by about 40 per cent, or from values of 7.7 to 10 for pressure ratios of 20,000 across the diaphragm. This increase is sufficient to produce partial dissociation of the oxygen molecules behind the shock wave. The flow behind the shock wave was as uniform as that produced by an unheated driver.

A transition section was designed to enable the major portion of the low pressure chamber to be constructed of round Shelby tubing, while the test section still had a flat top and a flat bottom. The flat surfaces are advantageous for optical studies and for convenience in instrumenting the tube. Despite the fact that the transition was gradual, disturbances were present in the flow in the test section, 18 inches downstream of the transition section.

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I. INTRODUCTION

This report discusses the design and evaluation of a method of directly heating the gas in a shock tube driver, in order to increase the shock Mach number. This heating is accomplished by means of electrical heating elements (Calrods) installed inside the driver. Theory shows that, for strong shock waves, the Mach number increases with the square root of the absolute temperature of the driver gas, for given pressure ratio. Thus, assuming that the gas can be heated to about 600 degrees centigrade, one might expect to increase the shock speed about 70 per cent. A heated helium driver would then be comparable in performance to cold hydrogen, while heated hydrogen should give about the same performance as a combustion driver.

The advantages one would expect to achieve with direct heating are (1) a less hazardous operation, (2) good driver uniformity, and (3) simple control of driver energy. In fact, except for the heating cycle, the operation is in all respects the same as the ordinary cold driver operation.

The method is, of course, quite inefficient insofar as energy utilization is concerned, since most of the electrical energy goes into heating the walls of the driver. However, energy utilization is not a factor in the present design, since its cost is but a small fraction of the operating cost per shot. Energy utilization is indirectly a factor, in that one would like to heat the gas quickly (i. e., heating times of the order of a few minutes), and one would like to obtain the highest possible gas temperatures. Both objectives are more closely approached by increasing the power and reducing heat loss to the tube walls, and these conditions correspond to more efficient energy utilization.

The shock tube design and related experiments which are reported here were carried out during 1956-57, while the author was at the California Institute of Technology. In addition to the heated driver performance, we report here some measurements on shock tube performance and flow quality at pressures down to 1 mm. Hg, as well as some experience with the problem of making transition from a round tube to a flat-sided one.

II. DESCRIPTION OF THE SHOCK TUBE

A. General

The shock tube used in this investigation was composed of a compression chamber, a diaphragm section, an expansion section, and a dump chamber (Figures 1 and 2). The flanges of the 4 foot compression chamber rested on two parallel pipes on which the compression chamber was free to slide to facilitate the changing of the diaphragms. The large flange of the diaphragm section rests on the same pipes to assure the alignment of the two sections. The test section was preceded by two 10 foot lengths of tubing, each of which was bolted to two tripods which were bolted to the floor. The 30 inch test section was suspended between the second 10 foot section and the dump chamber. The dump chamber was also bolted to the floor. For reflected shock experiments, the test section was not connected to the dump chamber, but was held securely by the flange connecting it to the second 10 foot section.

B. Compression Chamber

The compression chamber of this shock tube (Figure 3) was designed to provide for the uniform heating of the driver gas before diaphragm breakage. A quartz liner, 3/4 inch thick, was inserted in a steel tube which could withstand pressures in excess of 1500 psi. This liner insulated the driver gas from the steel tube. The quartz tube was anchored near the diaphragm section by a stainless steel pin, but otherwise could slide within the steel tube, which allowed for the differences in the thermal expansion of the steel and the quartz. A quartz plug, free to slide within the quartz tube, was anchored to the upstream flange.

The inside of the quartz tube was coated with several layers of Hanovia platinum paint in an effort to reflect radiant heat away from the walls of the tube. However, because of the roughness and porosity of the inner surface of the quartz, the paint darkened the walls and made them opaque. This darkening should have been of some help in preventing the radiant energy from the heater from going directly through the quartz to the steel tube. The inner surface could have been made reflective if the surface of the quartz had been glazed before applying the platinum paint.

Two high speed, high heat Calrod heaters, each consuming 3500 watts at 230 volts were used to heat the driver gas. These heaters were 98 inches total length and were bent in the form of elongated "U"s (Figure 3). The ends of the heaters were brought through the quartz plug and the flange at the end of the compression chamber and were brazed to the flange to form a leak-proof connection. They were supported at the downstream end by a sliding support to allow for the thermal expansion of the heaters. These heaters could serve up to compression chamber temperatures of approximately $600^{\circ}C$. With the power available at the time of the experiments, this temperature was never reached.

C. Diaphragm Section

The cross sectional view of the diaphragm section used is shown in Figure 3. The inside diameter of the quartz tube in the compression chamber was $2\frac{1}{2}$ inches, while the inside diameter of the low pressure tube was 2 inches. The diaphragm was located between the $2\frac{1}{2}$ inch round tube and a 2 inch square section. This design allowed the diaphragm to open along the diagonals of the square. The downstream side of the diaphragm was insulated by a quartz ring set into a stainless steel transition section which tapered from the 2 inch square to the 2 inch diameter circle.

For the reflected shock experiments it was found that the diaphragm leaves initially opened in the downstream direction and then were bent back into the compression chamber by the reflected shock. To protect the quartz liner, an additional steel flange $1\frac{1}{2}$ inches thick was inserted between the compression chamber and the diaphragm. This flange had a transition from a 2 inch round section to a 2 inch square section. The leaves of the diaphragm could blow back into this steel section and no longer strike the quartz. However, the steel conducted some heat away from the compression chamber. This section was used only for reflected shock experiments and was easily removable.

A removable flange could be installed between the diaphragm section and the first 10 foot length of the low pressure section. This flange had inlets for a pressure gage line, a vacuum line, and a line for introducing test gases other than air into the low pressure section; it was used when evacuating the low pressure section independently of the dump chamber. The vacuum line had a circle seal check valve which had been modified to act as a rate of flow valve. This valve stayed open during the evacuation of the tube, but closed when the shock wave entered the line after the diaphragm broke, in order to protect the vacuum lines from the high pressures which occurred in the expansion section during the reflected shock experiments. Test gases could be introduced from small chambers which were filled with a given volume of gas at some predetermined pressure. By properly adjusting this pressure, the pressure in the expansion section of the shock tube could be set at any desired value.

D. Expansion Section

The expansion section was composed of 2 10-foot lengths of 2 inch inside diameter, 1/4 inch wall, Shelby seamless steel mechanical tubing, followed by the test section. The tubing was cold finished and had a smooth finish on its inside surface. The junctions between the tubes were aligned by the use of male and female joints as shown in Figure 4. The downstream 10-foot length of tubing had 2 ports located 2 feet apart for heat transfer gages used to measure the speed of the shock wave. The Shelby tubing and the flanges were built to withstand pressures in excess of 200 psi.

Two test sections were used in these experiments. The first was a length of 2 inch inside diameter Shelby tubing 30 inches long. This tube had two ports 21 inches apart for mounting gages to measure the speed of the shock wave or installing models with heat transfer gages. The second test section was designed to have a flat top and bottom (Figure 4). This test section had parallel top and bottom surfaces $1\frac{1}{2}$ inches apart and sides composed of Shelby tubing with an inside diameter of 2-1/4 inches. This section was faired into the 2 inch inside diameter tubing with a smooth, gradual transition region. The cross-sectional area of the tube was the same as that of the 2 inch inside diameter tube. Two ports for heat transfer gages used to measure the wave speed were spaced 12 inches apart, immediately after the transition region. Windows were located downstream of these ports. A port for mounting a model was located just downstream of the top window.

E. Dump Chamber

A dump chamber was installed downstream of the test section, as may be seen in Figure 2. The entrance to the dump chamber had an 8 inch inside diameter to allow for possible replacement of the uniform test section by an expanding nozzle. The dump chamber was mounted vertically; therefore, any dirt in the tube would be blown to the bottom of the chamber. Pressure gage and vacuum lines were installed in the chamber.

F. Vacuum Pumps

A Welch Duo-Seal number 1428B mechanical pump and Consolidated Vacuum Corporation MCF 700-04 diffusion pump could be used to evacuate the tube to pressures of about 50 microns. Both pumps were used for experiments with pure gases. When air was used as a test gas, the mechanical pump alone was used to evacuate the expansion section to the desired pressure.

G. Instrumentation

The pressure of the driver gas was measured with a 2000 psi gage which was protected by a check valve from the sudden decrease in pressure after the rupture of the diaphragm. The temperature of the heated driver gas was measured with a Brown Pyrometer and two shielded thermocouples. One thermocouple was located near the diaphragm and the other near the upstream end of the chamber (Figure 3). A thermocouple was also soldered to the outside of the steel jacket at the middle of the compression chamber. This thermocouple indicated the maximum temperature of the outside of the steel tube during its operation.

The pressure in the expansion section before diaphragm rupture was measured with a 20 mm. Hg Wallace and Tiernan absolute pressure indicator. This gage, which was accurate to .05 mm. Hg was calibrated by comparison with a Macleod gage. When gases other than air were used as a test gas, the vacuum was checked with an Alphatron gage before introducing the test gas.

The velocity of the shock wave was determined by measuring the time it took the shock wave to travel between two wave speed ports. Resistance thermometers described by Rabinowicz in References 1 and 2 were used to detect the passage of the shock past a port. The signals from two such gages were amplified and fed into a Berkeley type 7360 counter. The gages were installed flush with the inside walls of the second 10 foot tube in the expansion section and in either of the two test sections. The platinum film was sputtered on pyrex cut from a 2 inch inside diameter, 1/4 inch tube, for mounting in the round tube.

III. PERFORMANCE OF THE HEATED COMPRESSION CHAMBER

A. General

The strength of the incident shock wave produced in a shock tube can be increased by raising the temperature of the driver gas. Figure 5 demonstrates the dependence of the shock strength on the pressure ratio, p_4/p_1, and the temperature ratio, T_4/T_1, for helium as the driver gas and air as the test gas. Conditions in the driver section, immediately before the diaphragm is ruptured, are denoted by the subscript 4 and conditions in the low pressure section by the subscript 1. In this investigation, the resistance heaters were used to heat the driver gas slowly and uniformly.

B. Method of Operation

The heat was added to the compression chamber by the Calrod heaters, while the quartz liner insulated the driver gas from the steel jacket. The heat capacity of the helium gas was much lower than that of the quartz liner. Therefore, almost all the energy went into heating the quartz. The temperature of the gas was estimated to be approximately the same as the temperature of the inside surface of the quartz. The temperature difference between the inside surface and the outside surface of the quartz was the value calculated using steady state heat transfer theory. This difference was directly proportional to the power input to the heaters; for the 7 kilowatts available, this difference was approximately 200°C. The maximum temperature of the inner surface of the quartz was therefore determined by the maximum temperature allowable on the outer surface of the quartz and the power available to the heaters.

To obtain the maximum heating in actual operation, the helium driver gas was introduced into the chamber at about 1/3 the desired bursting pressure of the diaphragm. The power was then turned on and the driver gas and the quartz were heated. The heat diffused through the quartz and after approximately 15 minutes, the steel jacket reached a temperature of 110°C. At this time, helium was slowly added to increase the pressure until the diaphragm ruptured. This did not cool the driver gas because the heat capacity of the helium was low and it was introduced over a period of about 60 seconds. The power was then turned off and the cooling water was turned on. The steel jacket reached a maximum temperature just below the melting point of the solder holding the cooling coils in place, or about 120°C.

C. Experimental Program

The shock wave Mach number was measured using two sets of two resistance thermometers mounted flush with the wall of the tube. The first two thermometers were located $11\frac{1}{2}$ feet and $13\frac{1}{2}$ feet from the diaphragm; the second set, $21\frac{1}{2}$ and 23-1/4 feet from the diaphragm. The first two gages were wired in series and the voltage drop for a constant current was measured with a Tektronix type 535 oscilloscope. The sweep rate of the oscilloscope was set and checked with the timing pulse taken from the Berkeley counter. The shock wave velocity could be determined to an accuracy of better than 1 per cent using this method. A sample trace is shown in Figure 6 where the output of the gages was fed into the scope through a resistance capacitance circuit. The outputs of the second two gages were fed into the Berkeley counter as described in Reference 1. The accuracy of the counter is $\pm$ .5 per cent for the Mach numbers used in this investigation.

The tube was operated with the compression chamber both hot and cold. The shock wave Mach number, $Ms_{12\frac{1}{2}}$, between the $11\frac{1}{2}$ foot and $13\frac{1}{2}$ foot stations is plotted versus the pressure ratio, p_4/p_1, in Figure 5. Maximum available heating power was used for the heated compression chamber data. The shock wave Mach number, $Ms_{12\frac{1}{2}}$, between the $11\frac{1}{2}$ foot and $13\frac{1}{2}$ foot stations is plotted versus the shock wave Mach number, $Ms_{22\frac{1}{2}}$, between the $21\frac{1}{2}$ foot and 23-1/4 foot stations in Figure 7.

D. Experimental Results

The temperature of the helium in the compression chamber could not be accurately measured. The thermocouples initially were exposed to the radiation of the Calrod heaters and the temperatures measured were excessive. The thermocouples were then shielded and the temperatures measured were lower although still in excess of the value indicated by the shock speed measurements. The thermocouples at both ends of the tube did give the same value of the temperature within $10^{\circ}C$, which is an indication that the temperature was uniform along the length of the compression chamber. The temperatures could not be checked by observing the increase in the pressure of the gas in the compression chamber during the heating process because there were leaks in the system.

The shock wave attenuation was checked for both the heated and the unheated driver. The results of this investigation are shown in

Figure 7 where the shock wave Mach number at the $12\frac{1}{2}$ foot station is plotted against the Mach number at the $22\frac{1}{2}$ foot station. The experimental points are seen to all lie along a line representing 5 per cent attenuation over the 10 foot interval. The variation from this line with heating or varying pressure levels was less than the accuracy of the measurements. P_4 was held between 400 and 600 psi for all the shots. P_1 varied from 0.8 mm. Hg to 20 mm. Hg for both the hot and cold shots. Therefore, the flow in the tube using the heated driver was as uniform as that using the cold driver. If any waves were produced due to the heating, they would have accelerated or decelerated the shock wave. The absence of such waves is a further indication that the compression chamber was uniformly heated.

The effect of heating on the shock wave Mach number is shown in Figure 5. The theoretical curves for temperature ratios, T_4/T_1, of 1, 2, and 3 are plotted along with the experimental points for both heated and cold shots. The theoretical curves were not corrected for imperfect gas effects, differences in the cross sectional areas of the compression chamber and the low pressure section, or shock wave attenuation. The cross sectional area of the compression chamber is 50 per cent greater than that of the low pressure section. By referring to Figure 14 of Reference 3, one sees that this as a ratio corresponds to a gain in the pressure ratio of 20 per cent or an increase in Mach number of less than 2 per cent. The attenuation studies indicate that the shock wave attenuates at least 5 per cent in the $12\frac{1}{2}$ feet between the gages and the diaphragm. No estimate was made for the correction for imperfect gas effects. However, ignoring all corrections, the observed Mach numbers were in excess of the theoretical Mach numbers for the cold shots. This behavior was also observed by Rabinowicz in the 3 inch square shock tube (Figure 23, Reference 1).

The shock wave Mach number was increased with heating. The experimental Mach numbers for maximum heating scatter around the theoretical curve corresponding to a temperature ratio, T_4/T_1, of 2. The thermocouples indicated temperatures over 400°C in the compression chamber, but comparing the experimental results with the theory for both the hot and cold shots indicate that the effective shock speeds corresponded to values of T_4 of approximately 300°C.

E. Discussion of the Heated Compression Chamber

The heated compression chamber raised the Mach number from the unheated value of 7.7 to a heated value of 10 for a pressure ratio, p_4/p_1, of 20,000. This increase is great enough to permit study of the effects of the dissociation of the oxygen molecules of the air (Figure 4, Reference 4). The shock wave attenuation was unchanged from that observed using the cold driver for similar Mach numbers (Figure 7). Wittliff and Wilson of the Cornell Aeronautical Laboratories (Reference 5) observed a greater and varying attenuation of the shock wave using combustion drivers.

The maximum temperature ratio, T_4/T_1, obtained might be increased by increasing the power available, by increasing the efficiency of the insulators lining the steel jacket, or by increasing the maximum allowable temperature of the steel jacket. The quartz liner was chosen as an insulator because of its resistance to thermal shock, however, it chipped easily. A redesign of the compression chamber not employing a quartz liner would be advisable.

IV. PERFORMANCE OF THE TEST SECTIONS

A. General

Two test sections were used in these experiments. The first was merely an extension of the 2 inch internal diameter tubing of the low pressure section. This section was used to study the flow in the basic tube with no disturbances caused by a change in cross section. The second test section had a transition from the round tube to a tube with flat top and flat bottom surfaces but with no change in cross sectional area. A drawing of this test section is shown in Figure 4. The flat surfaces are desirable for mounting windows, gages and models. However, it is more convenient to construct the low pressure section of round tubing. The second test section was an attempt to use round tubing for the major portion of the low pressure section and then make a transition to a test section with flat surfaces.

B. Instrumentation

The stagnation point heat transfer gages described in References 1 and 2 were used to estimate the duration of uniform flow in both test sections. The schlieren system used the same spark source described in Reference 1. The 2 microsecond spark was triggered by a platinum resistance thermometer through an electronic time delay. A shutter which could be opened from the control room was mounted on the camera. All components of the schlieren system were securely fastened to the floor or walls of the room to prevent the vibration of the tube from disturbing the adjustment of the system. One man could operate the shock tube from the lighted control room while the room containing the test section was kept dark.

C. Flow Measurements

The duration of uniform flow in both test sections was determined from the output of stagnation point heat transfer gages. Typical outputs are shown in Figure 8. The output represents the surface temperature of the stagnation point heat transfer gage. For a constant heat input corresponding to constant enthalpy flow, the temperature rise should be parabolic after the initial jump at the shock wave. If the flow is non-uniform, the smooth parabolic trace will be distorted. The uniform flow time was measured by determining the time between the passage of the shock wave and the first disturbance of the trace from the parabolic rise. The uniform flow time is plotted against the Mach number in Figure 9 for both the round and the flat top and bottom test sections. The flow in the flat top and bottom test section appeared non-uniform even before the major disturbance as is seen in the unevenness of the rise in the temperature in Figure 8. The temperature rise in the round test section was uniform as can be seen in the smoothness in the temperature rise.

The change in the shock wave Mach number in traversing the transition section from the round to the flat-sided test section was measured, using two sets of wall heat transfer gages. The shock wave Mach number in the test section is compared with the shock wave Mach number 2 feet upstream of the transition section in Figure 10. The accuracy of the measurements was the same as that for the attenuation studies, or approximately $\pm$ 1 per cent. The shock wave attenuated

2 per cent between the two sets of gages set $2\frac{1}{2}$ feet apart. The shock wave attenuation in the round tube was 5 per cent over a 10 foot length. We would therefore expect an attenuation of 1-1/4 per cent in $2\frac{1}{2}$ feet of straight round tube. The shock wave attenuated more through the transition section than it would for a straight tube. This occurred despite the equal cross sectional areas between the two sections. Thus the transition section has some small effect on the shock speed.

The flow in the flat top and bottom test section was also studied by observing the flow over wedges and cones using schlieren techniques. Typical schlieren photographs are shown in Figure 11. The side walls of the tube were circular and cannot be observed in the picture. The windows were 1-3/4 inches wide and the inside diameter of the sidewalls was 2-1/4 inches. The wave angles of the shock waves produced by the cone and wedge were measured and used to calculate the Mach number of the air flowing over the models. Perfect gas theory was assumed for these calculations. These Mach numbers are plotted against the time after the passage of the shock wave past the models in Figure 12. The wave angles vary, again indicating the non-uniformity of the flow shown by the stagnation point heat transfer gages. The large variation in Mach number corresponds, in time, to the large disturbances shown by the heat transfer gages.

V. CONCLUSIONS

A. Heated Compression Chamber

The increase in shock wave strength corresponded to an increase in driver temperature of about 300°C. The shock wave attenuated at the same rate as it did with the cold driver, i. e., the attenuation was about $\frac{1}{2}$ per cent per foot, for shock Mach numbers from 5 to 10 and initial expansion chamber pressures from 1 to 20 mm. Hg. No disturbance in the flow was observed due to the heating, showing that the compression chamber was heated evenly over its length. This conclusion was also verified by the thermocouples located at both ends of the compression chamber. The quartz liners used in the compression chamber chipped during the operation of the tube and proved unsatisfactory.

B. Test Sections

In an attempt to construct the major length of the expansion section of round tubing and still have the advantages of two flat parallel sides in the test section, a test section was designed with a flat top and flat bottom. This cross section was preceded by a transition section which tapered into the round tube. The cross sectional area of the tube was held constant. However, the flow was non-uniform after this transition section as shown both by stagnation point heat transfer gages and schlieren photographs, so that it does not seem possible to make such a transition near the test section, even when there is no area change, and the fairing is quite gradual.

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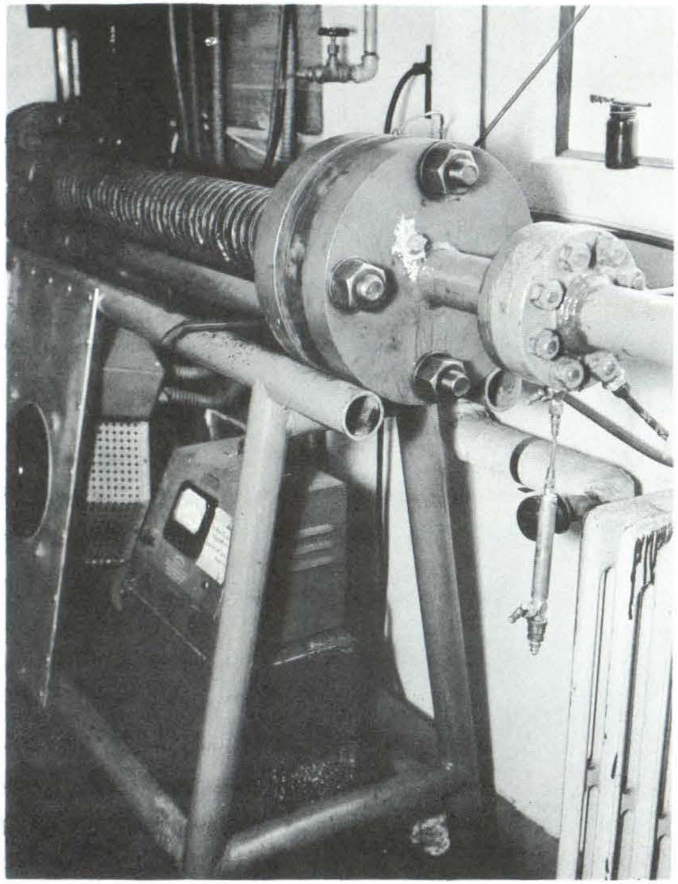
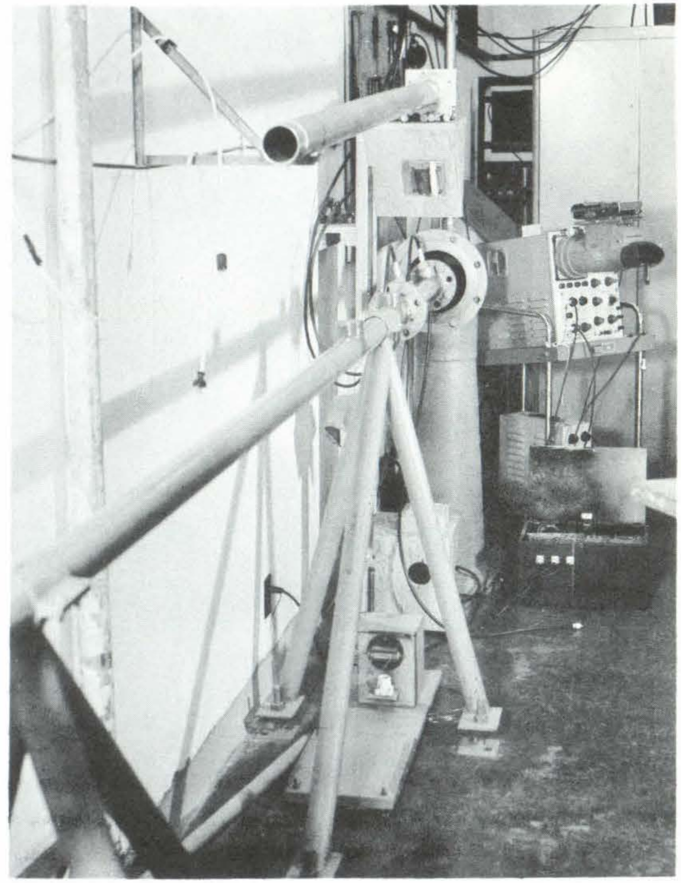


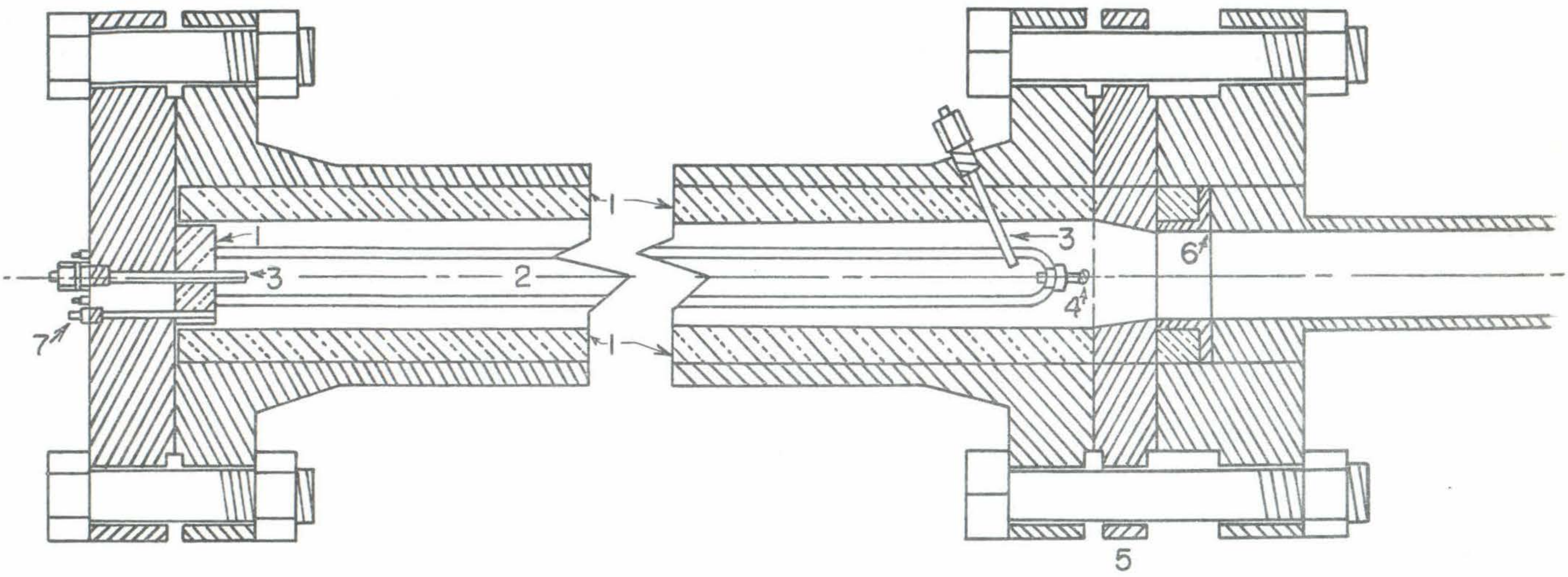
Coils on driver are for circulating cooling water. Small flange at right carries parts for introducing gases.

FIG. 1 DRIVER SECTION



Two resistance film gage mounts on the test section are visible. Tube in upper part of picture is part of the schlieren system.

FIG. 2 TEST SECTION AND DUMP CHAMBER (view looking downstream)



1. Quartz Liner
2. Two G.E. Calrod Heaters
3. Thermocouples
4. Front Support Pin For Quartz And Calrod
5. Removable Diaphragm Section For Reflected Expt.
6. Transition Section From 2" Square To 2" Dia. Round
7. Gas Inlet

FIG. 3 - HEATED COMPRESSION CHAMBER

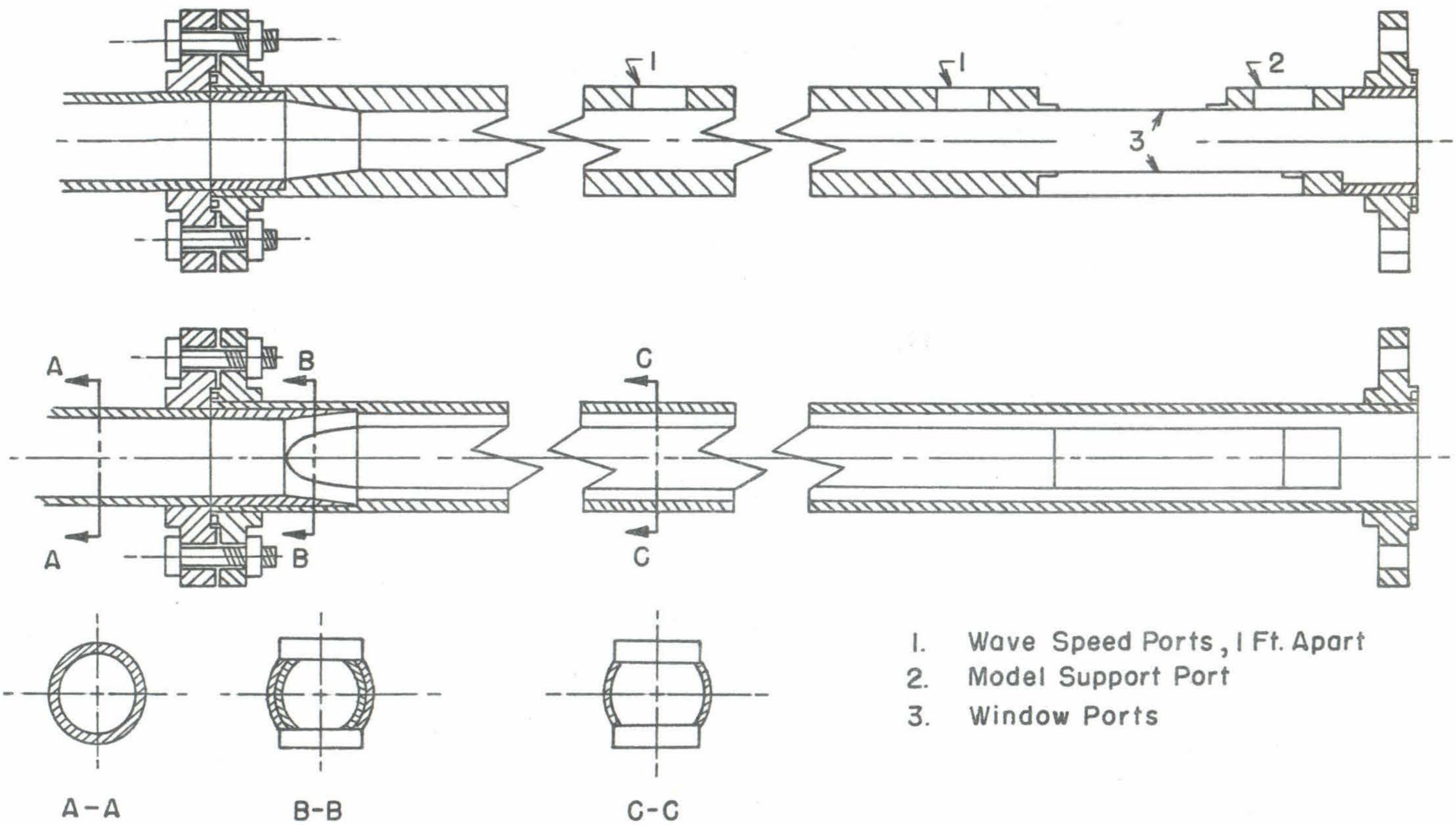


FIG. 4 - FLAT TOP AND BOTTOM TEST SECTION

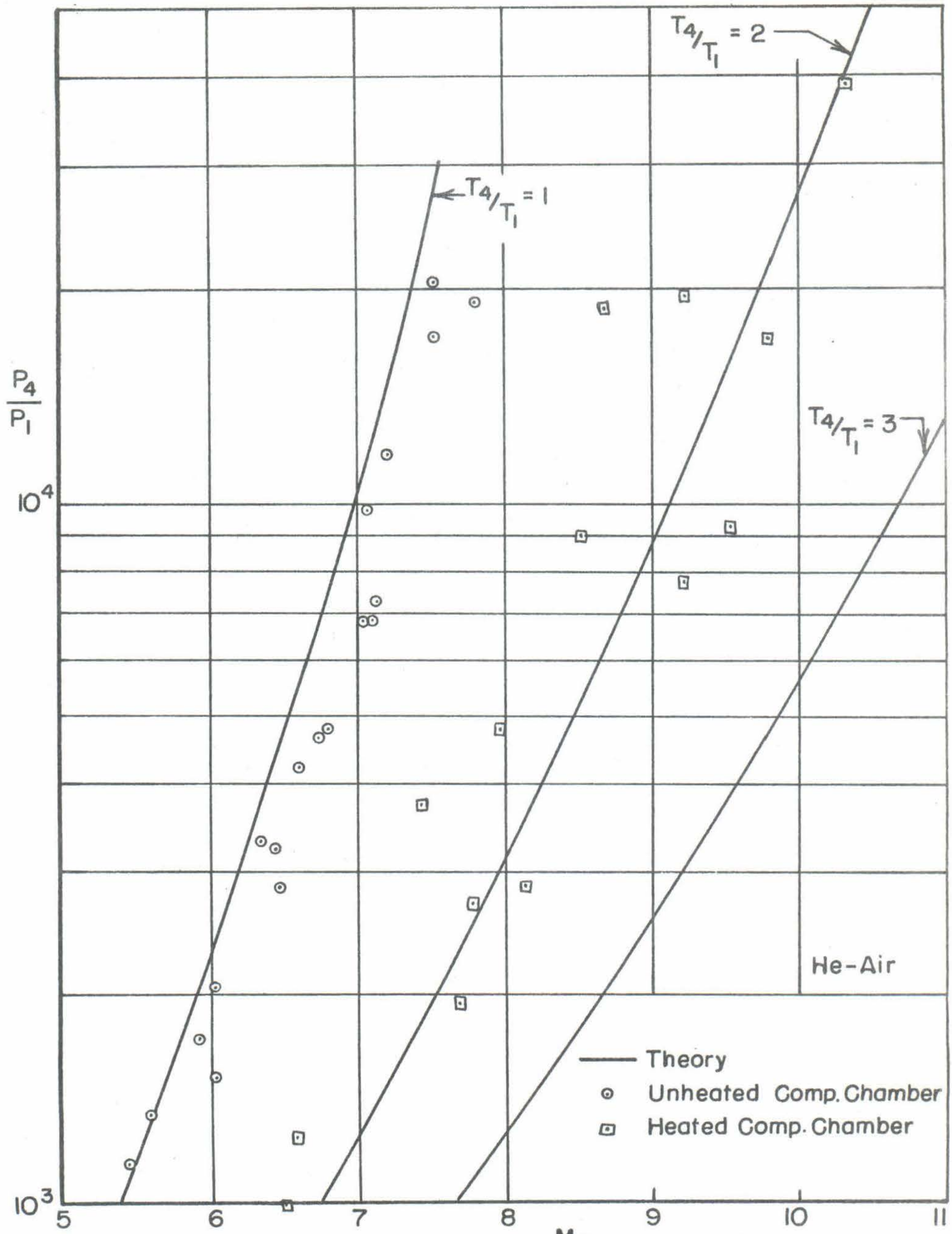
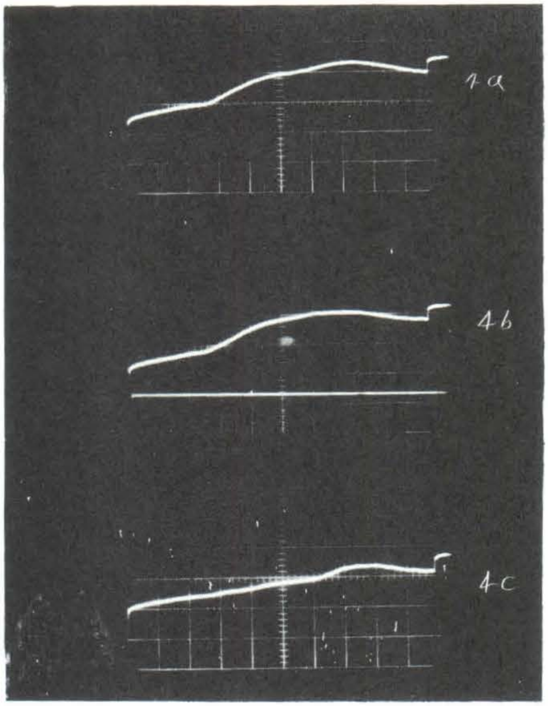
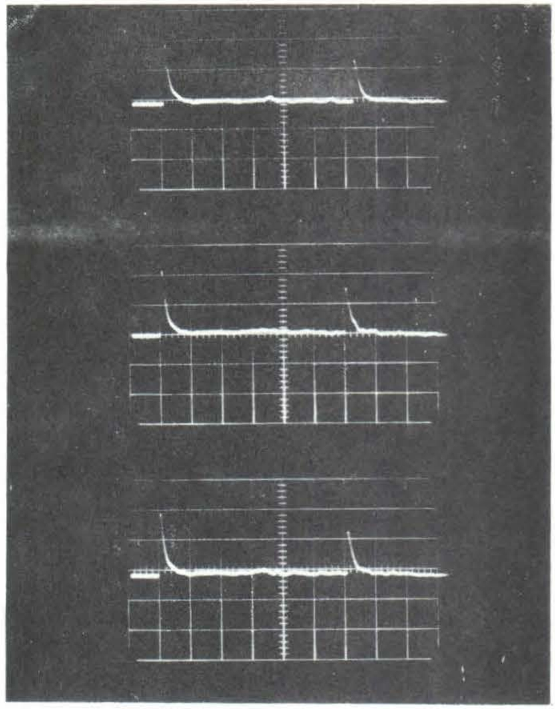


FIG. 5 — SHOCK WAVE MACH NUMBER vs. PRESSURE RATIO



2 Wall Resistance Thermometers
Wired in Series
in Round Test Section

Sweep: 30 μ sec./div.
Ports: 21" apart
t = 290 μ sec.
= 290 μ sec.
= 296 μ sec.



2 Wall Resistance Thermometers
Wired in Series with R. C. Circuit
in Flat-Sided Test Section

Sweep: 20 μ sec./div.
Ports: 12" apart
t = 124 μ sec.
= 120 μ sec.
= 122 μ sec.

FIG. 6 EXAMPLES OF OUTPUT OF WALL RESISTANCE GAGES USED FOR WAVE SPEED MEASUREMENT

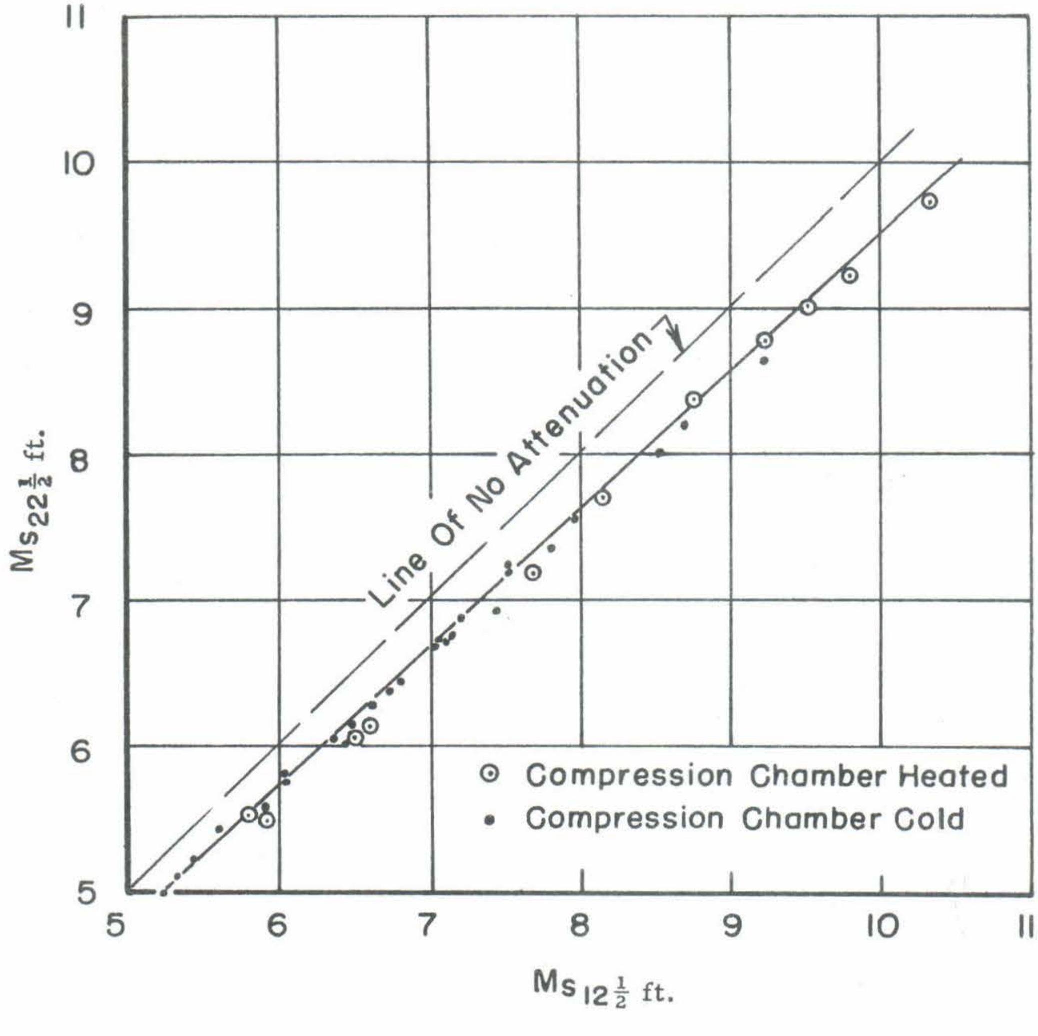
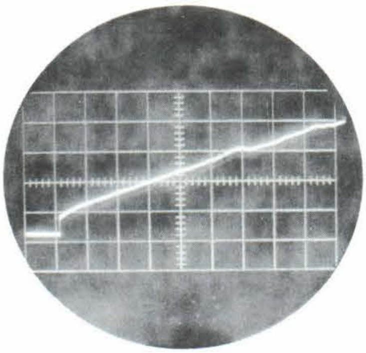
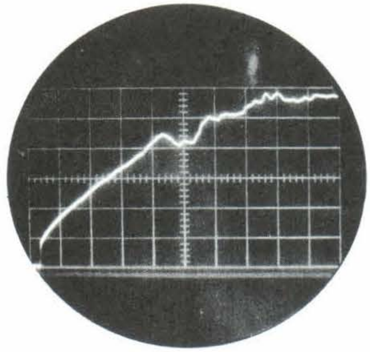


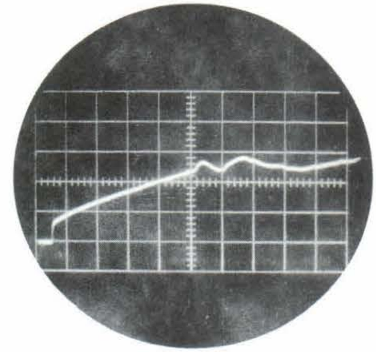
FIG. 7 – SHOCK WAVE ATTENUATION IN 2" DIA. ROUND TUBE



$M_s = 5.17$
$p_1 = 17.8$ mm. Hg.
(50 μ s; .100 v; 20 ma)

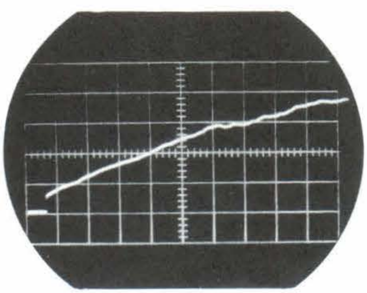


$M_s = 6.85$
$p_1 = 2.5$ mm. Hg.
(50 μ s; .050 v; 20 ma)

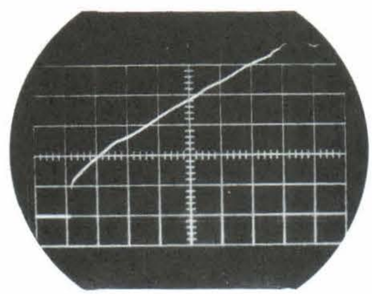


$M_s = 7.10$
$p_1 = 1.1$ mm. Hg.
(20 μ s; .050 v; 20 ma)

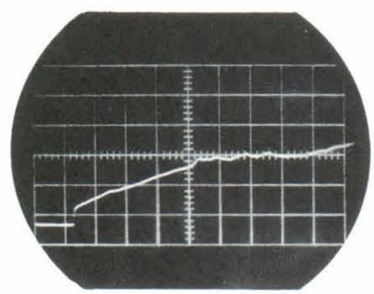
ROUND TEST SECTION



$M_s = 5.27$
$p_1 = 15.8$ mm. Hg.
(50 μ s; .100 v; 20 ma)



$M_s = 6.83$
$p_1 = 1.3$ mm. Hg.
(20 μ s; .025 v; 20 ma)



$M_s = 7.23$
$p_1 = 0.8$ mm. Hg.
(20 μ s; .050 v; 20 ma)

FLAT-SIDED TEST SECTION

FIG. 8 STAGNATION HEAT TRANSFER

(The numbers in parentheses give the sweep rate in microseconds per large div., the sensitivity in volts/div., and heating current in milliamp.)

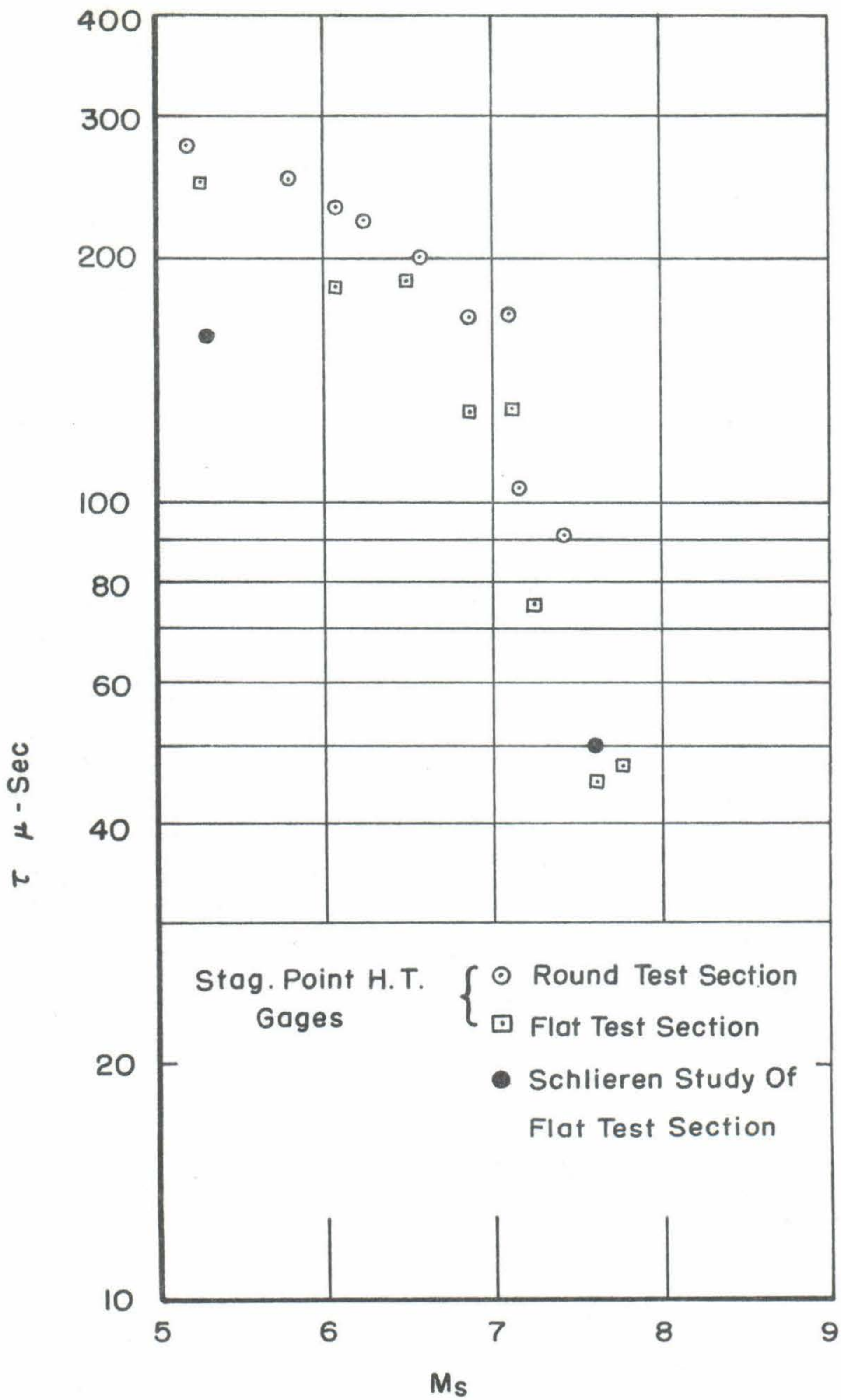


FIG. 9 – UNIFORM FLOW TIME vs. SHOCK MACH NUMBER

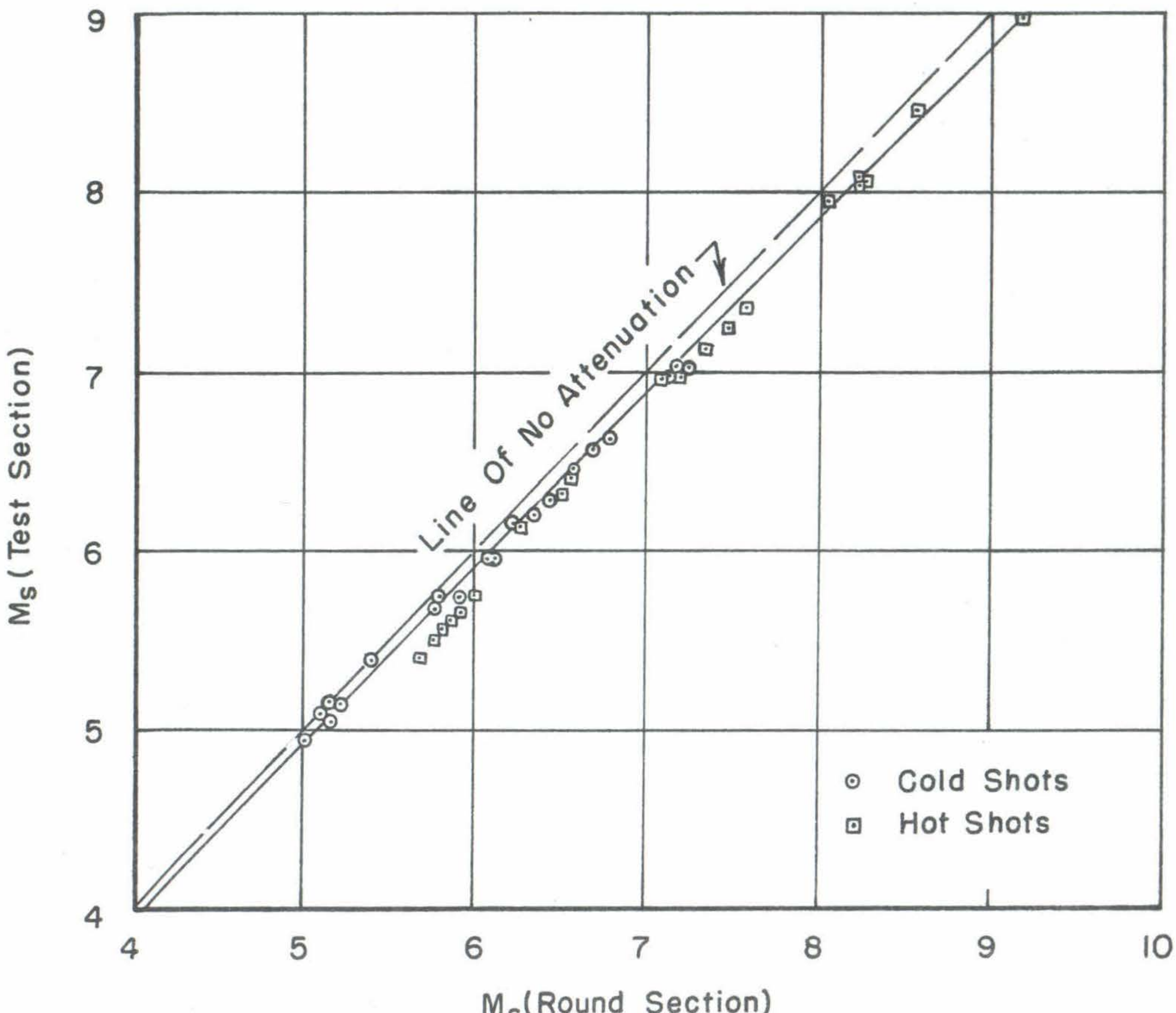
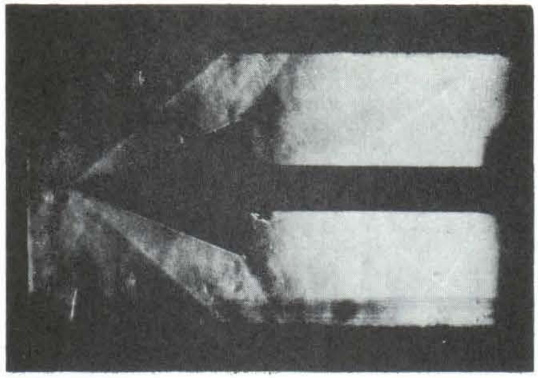
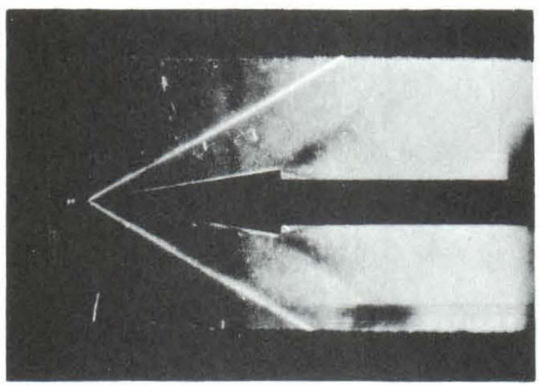


FIG. 10- FLAT TOP AND BOTTOM TEST SECTION MACH NUMBER VS. MACH NUMBER IN ROUND TUBE 1 1/2 FEET UPSTREAM OF TEST SECTION



Flow over 45° Cone

$M_s = 5.4$; $p_1 = 8.9$ mm. Hg.



Flow over 20° Wedge

$M_s = 9.2$; $p_1 = 3.1$ mm. Hg.

FIG. 11 SCHLIEREN PHOTOGRAPHS OF FLOW IN TEST SECTION

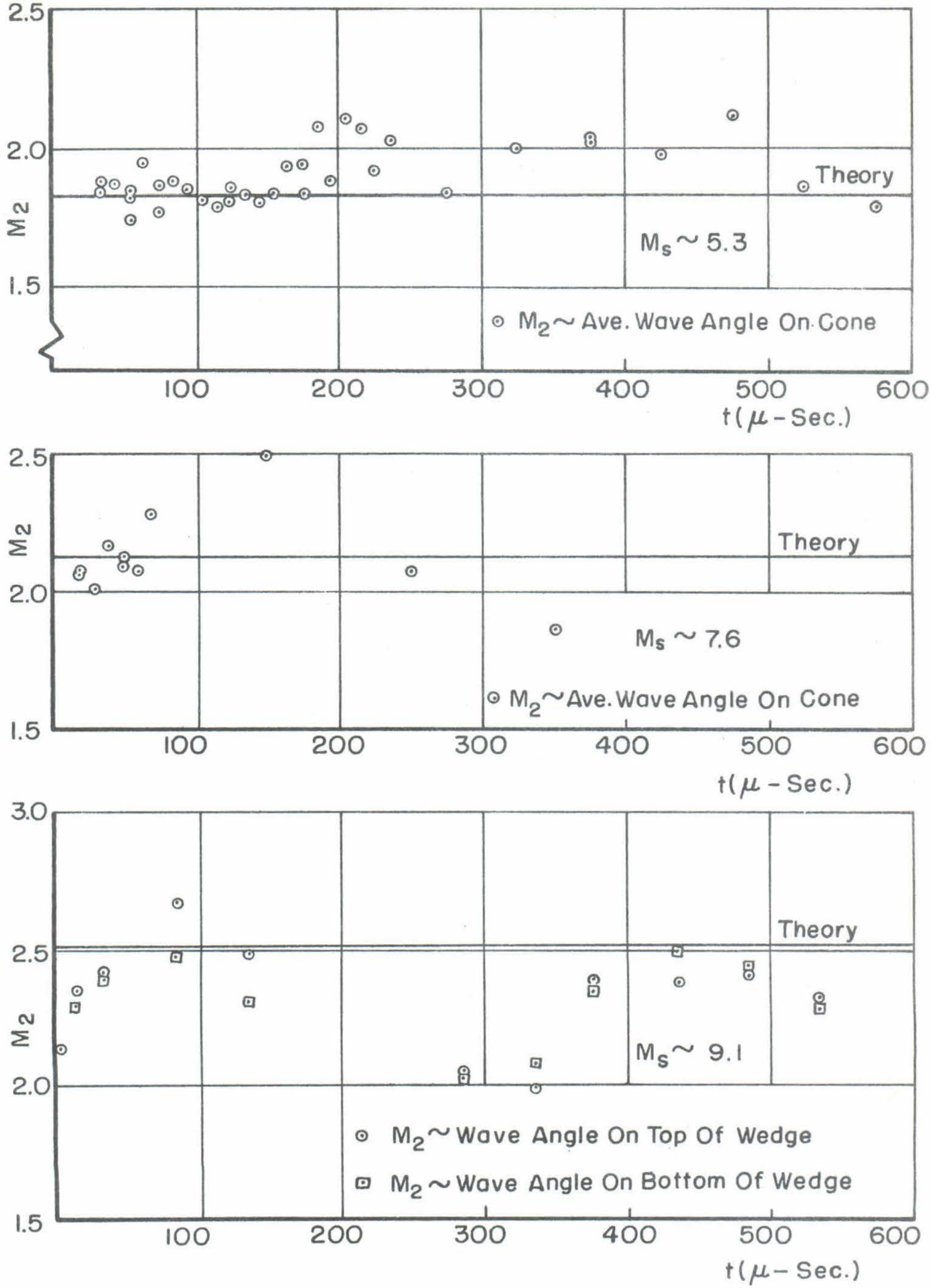


FIG. 12 - TEST SECTION MACH NO. vs. TIME AFTER SHOCK PASSAGE

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